HEAVY QUARK SPECTROSCOPY AT LHCb

SIMON EIDELMAN

for the LHCb Collaboration

*Budker Institute of Nuclear Physics SB RAS, Novosibirsk 630090, Russia
 and Novosibirsk State University, Novosibirsk 630090, Russia*

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We report recent results related to spectroscopy of heavy quarks obtained with the LHCb detector. They include a study of the $X(3872)$ produced in continuum and B decays, precise measurements of the D and D_s masses, a study of the properties of D_J mesons and excited B_s states as well as the first observation of the $B_c^+ \rightarrow B_s^0 \pi^+$ decay.

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1. Introduction

LHCb,¹ the detector at the LHC pp collider, is a single-arm forward spectrometer at $2 < \eta < 5$ for a study of particles with b or c quarks. The integrated luminosity it collected is 37 pb^{-1} and 1.0 fb^{-1} at 7 TeV (in 2010 and 2011, respectively) and 2 fb^{-1} at 8 TeV. In this talk we briefly describe several recent analyses related to spectroscopy of heavy c and b quarks.

2. Study of the $X(3872)$ State

LHCb performed its first study of the $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ using 34.7 pb^{-1} of integrated luminosity collected at $\sqrt{s} = 7 \text{ TeV}$.² They measured the cross section of its production in continuum $\sigma(pp \rightarrow X + \text{anything}) \mathcal{B}(X \rightarrow J/\psi \pi^+ \pi^-) = 5.4 \pm 1.3(\text{stat}) \pm 0.8(\text{syst}) \text{ nb}$ at $2.5 < \eta < 4.5, 5 < p_T < 20 \text{ GeV}/c$ and observe a clear signal of the $X(3872)$ (565 ± 62) in addition to the $\psi(2S)$ (3998 ± 83), see Fig. 1. For both particles the values of the mass they obtain are consistent with those in the most precise previous measurements (KEDR for $\psi(2S)$ ³ and CDF for $X(3872)$ ⁴).

In their second study they use a data sample of 1 fb^{-1} to select 313 ± 26 events of $B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow J/\psi \pi^+ \pi^-$. They perform a 5-dimensional analysis

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Fig. 1. Distribution of the $J/\psi\pi^+\pi^-$ mass

of the angular space and come to the unambiguous conclusion about the quantum numbers of the $X(3872)$: $J^P = 1^+$.⁵

With a data sample of 3 fb^{-1} at 7 and 8 TeV they study $B^+ \rightarrow K^+\mu^+\mu^-$ decays and select 1830 candidates in the low recoil region ($m_{\mu^+\mu^-} > 3770 \text{ MeV}$). In the $m_{\mu^+\mu^-}$ spectrum they observe a structure with more than 6σ significance, which properties (mass of $4191^{+9}_{-8} \text{ MeV}$ and width of $65^{+22}_{-16} \text{ MeV}$) are consistent with the $\psi(4160)$. This is the first observation of the $\psi(4160) \rightarrow \mu^+\mu^-$ decay.⁶

3. Study of D and D_{sJ} Mesons

3- and 4-body decays of charm mesons produced in semileptonic b -hadron decays were studied in pp collisions at $\sqrt{s} = 7 \text{ TeV}$ with 1 fb^{-1} – $D^0 \rightarrow K^+K^-\pi^+\pi^-$, $D^0 \rightarrow K^+K^-K^-\pi^+$, $D^+ \rightarrow K^+K^-\pi^+$ and $D_s^+ \rightarrow K^+K^-\pi^+$. These modes have a relatively low energy release, the difference between the mass of the D meson and the sum of the masses of the daughter particles, resulting in reduced systematic uncertainties due to the calibration of the momentum scale and thus a high-precision measurement of the D^0 , $D^\pm$ and D_s^+ mass and mass differences.⁷ As an example, Fig. 2 shows the invariant mass distributions for the $K^+K^-\pi^+\pi^-$ and $K^+K^-K^-\pi^+$ final states together with the corresponding fits.

The results of the fits are used to determine $M(D^0)$, $M(D^+) - M(D^0)$ and $M(D_s^+) - M(D^+)$ shown in Table 1, which also lists the best previous measurements as well as the results of the PDG fit.¹¹ Including the result for the D^0 mass in the determination of the $X(3872)$ binding energy gives $E_B = M(D^0 D^{*0}) - M(X(3872)) = 0.09 \pm 0.28 \text{ MeV}$ and reinforces the conclusion that if the $X(3872)$ is a molecule, it is extremely loosely bound.

These measurements, together with others listed by PDG, can be used to determine a more precise value of the D_s^+ mass, $M(D_s^+) = 1968.19 \pm 0.20 \pm 0.14 \pm 0.08$

Table 1. Measurement of the D and D_s masses

Quantity	LHCb measurement	Best previous measurement	PDG fit
$M(D^0)$	1864.75 ± 0.19	1864.85 ± 0.18 CLEO ⁸	1864.86 ± 0.13
$M(D^+) - M(D^0)$	4.76 ± 0.14	4.7 ± 0.3 MARK2 ⁹	4.76 ± 0.10
$M(D_s^+) - M(D^+)$	98.68 ± 0.05	98.4 ± 0.3 BaBar ¹⁰	98.88 ± 0.25

MeV, which is more precise than that obtained from the fit to open charm mass data $M(D_s^+) = 1968.49 \pm 0.32$ MeV.¹¹

A study of $D^+\pi^-$, $D^0\pi^+$ and $D^{*+}\pi^-$ final states is performed using a data sample of 1.0 fb^{-1} collected at 7 TeV. The $D_1(2420)^0$ resonance is observed in the $D^{*+}\pi^-$ final state and the $D_2^*(2460)$ resonance is observed in the $D^+\pi^-$, $D^0\pi^+$ and $D^{*+}\pi^-$ final states. For both resonances, their properties and spin-parity assignments are obtained. In addition, two natural parity and two unnatural parity resonances are observed in the mass region between 2500 and 2800 MeV. Further structures in the region around 3000 MeV are observed in all the $D^+\pi^-$, $D^0\pi^+$ and $D^{*+}\pi^-$ final states.

4. Decays of B_s^0 and B_c

Orbitally excited ($L = 1$) B_s^0 states were studied at 7 TeV with 1.0 fb^{-1} .¹⁴ Figure 3 shows the mass difference distribution $m(B^+K^-) - m(B^+) - m(K^-)$. The left and right peaks correspond to the previously observed decays $B_{s1} \rightarrow B^{*+}K^-$ and

Fig. 2. Invariant mass distributions for the (a) $K^+K^-\pi^+\pi^-$ and (b) $K^+K^-K^-\pi^+$ final states.

Table 2. Polarization properties of the D_J resonances

Resonance	J^P (Function)	h parameter
$D_1(2420)^0$	$1^+(1 + h \cos^2 \theta_H)$	3.30 ± 0.48
$D_2^*(2460)^0$	$2^+(\sin^2 \theta_H)$	—
$D_J^*(2650)^0$	Nat. $(\sin^2 \theta_H)$	—
$D_J^*(2760)^0$	Nat. $(\sin^2 \theta_H)$	—
$D_J(2580)^0$	Unnat. $(1 + h \cos^2 \theta_H)$	4.2 ± 1.3
$D_J(2740)^0$	Unnat. $(1 + h \cos^2 \theta_H)$	3.1 ± 2.2
$D_J(3000)^0$	Unnat. $(1 + h \cos^2 \theta_H)$	1.5 ± 0.9

Fig. 3. Mass difference distribution $m(B^+ K^-) - m(B^+) - m(K^-)$

$B_{s2}^* \rightarrow B^+ K^-$, respectively, whereas that in the middle is identified as a new decay mode $B_{s2}^* \rightarrow B^{*+} K^-$.

A fit of the distribution gives the values of the difference from which, using $m(B^+)$, $m(B_{s1})$ and $m(B^{*+}) - m(B^+)$, one obtains:

$$\begin{aligned} m(B^*) &= 5324.26 \pm 0.30 \pm 0.23 \pm 0.17 \text{ MeV}, \\ m(B_{s1}) &= 5828.40 \pm 0.04 \pm 0.04 \pm 0.41 \text{ MeV}, \\ m(B_{s2}^*) &= 5839.99 \pm 0.05 \pm 0.11 \pm 0.17 \text{ MeV}. \end{aligned}$$

The more precise value of the $m(B^{*+})$ mass allows to determine that $m(Z_b(10610)at^+)$ and $m(Z_b(10650)^+)$ are 3.69 ± 2.05 MeV and 3.68 ± 1.71 MeV above the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds. One more important result is the first measurement of the B_{s2}^* width. Finally, the observation of $B_{s2}^* \rightarrow B^{*+} K^-$ and $B_{s2}^* \rightarrow B^+ K^-$ favors $J^P = 2^+$.

The B_c^+ meson is the ground state of the $\bar{b}c$ system, the only weakly decaying doubly heavy meson. All B_c^+ meson decays known to date are decays in which the constituent b quark decays weakly to a c quark. It is interesting to look for a decay of the B_c^+ meson to another B meson with the bottom quark acting as a spectator. For this search LHCb used a data sample of pp collisions corresponding to an integrated luminosity of 1 fb^{-1} taken at a center-of-mass energy of 7 TeV, and 2 fb^{-1} taken at 8 TeV.¹⁵ As a result of the analysis, the decay $B_c^+ \rightarrow B_s^0 \pi^+$ has been observed using two decay modes of the B_s^0 : $B_s^0 \rightarrow D_s^- \pi^+$, $D_s^- \rightarrow K^+ K^- \pi^-$ with a 7.5σ significance and $B_s^0 \rightarrow J/\psi \phi$, $J/\psi \rightarrow \mu^+ \mu^-$, $\phi \rightarrow K^+ K^-$ with a 5.5σ significance, see Fig. 4. This is the first observation of the weak decay of a B meson decaying to another B , with the b quark acting as a spectator

5. Summary

- $X(3872)$ is clearly selected both in continuum and B decays
- $X(3872)$ quantum numbers are 1^+

Fig. 4. $B_s^0 \pi^+$ invariant mass distribution for the (a) $B_s^0 \rightarrow D_s^- \pi^+$ and (b) $B_s^0 \rightarrow J/\psi \phi$

- Precise determination of D meson masses
- Various D_J were observed with J^P analysis
- Excited B_s states were studied
- Decay $B_c^+ \rightarrow B_s^0 \pi^+$ was observed
- Due to the high cross section, thus huge statistics, and excellent performance LHCb has a high potential for spectroscopy studies

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References

1. A. Augusto Alves, Jr. *et al.*, *JINST* **3**, S08005 (2008).
2. LHCb Collab. (R. Aaij *et al.*), *Eur. Phys. J. C* **72**, 1972 (2012).
3. KEDR Collab. (V.V. Anashin *et al.*), *Phys. Lett.* **711**, 280 (2012).
4. CDF Collab. (T. Aaltonen *et al.*), *Phys. Rev. Lett.* **103**, 152001 (2009).
5. LHCb Collab. (R. Aaij *et al.*), *Phys. Rev. Lett.* **110**, 222001 (2013).
6. LHCb Collab. (R. Aaij *et al.*), *Phys. Rev. Lett.* **111**, 112003 (2013).
7. LHCb Collab. (R. Aaij *et al.*), *JHEP* **1306**, 065 (2013).
8. CLEO Collab. (C. Cawfield *et al.*), *Phys. Rev. Lett.* **98**, 092002 (2007).
9. MARK2 Collab. (R.H. Schindler *et al.*), *Phys. Rev. D* **24**, 78 (1981).
10. BaBar Collab. (B. Aubert *et al.*), *Phys. Rev. D* **78**, 011103 (2008).
11. Particle Data Group (J. Beringer *et al.*), *Phys. Rev. D* **86**, 010001 (2012).
12. LHCb Collab. (R. Aaij *et al.*), *JHEP* **1309**, 145 (2013).
13. BaBar Collab. (P. del Amo Sanchez *et al.*), *Phys. Rev. D* **82**, 111101 (2010).
14. LHCb Collab. (R. Aaij *et al.*), *Phys. Rev. Lett.* **110**, 151803 (2013).
15. LHCb Collab. (R. Aaij *et al.*), *Phys. Rev. Lett.* **111**, 181801 (2013).